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NIST facility for Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources

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Abstract. A laser-based facility has been developed to provide high-flux, monochromatic, Lambertian radiation over the spectral range 0.2 µm to 18 µm. The facility was designed to reduce the uncertainties in a variety of radiometric applications, including irradiance and radiance responsivity calibrations. The operational characteristics of the facility are discussed and the results of detector responsivity calibrations over the spectral range 0.406 µm to 0.920 µm are presented.

1. Introduction

The increasing variety and complexity of detector-based radiometric applications have led to the need for reduced uncertainties in detector power, irradiance and radiance measurements. Detector responsivity calibrations in the visible and near-infrared wavelength regions are performed at the National Institute of Standards and Technology (NIST) in the Spectral Comparator Facility (SCF) [1]. This is a lamp-monochromator-based facility typically used to calibrate test detectors for spectral power responsivity by direct substitution against calibrated reference detectors. In the visible wavelength region, from 406 nm to 920 nm, the relative combined standard uncertainties in power responsivity measurements are approximately 10^{-3} [1]. For power responsivity measurements outside this spectral range and for detector irradiance and radiance responsivity calibrations, the uncertainty increases significantly. For the spectral ranges 200 nm to 406 nm in the ultraviolet (UV) and 920 nm to 1800 nm in the infrared (IR), the relative combined standard uncertainty in spectral power responsivity measurements increases to between 5×10^{-3} and 10^{-2}. The relative combined standard uncertainty in irradiance responsivity calibrations is of the order of 5×10^{-3} in the visible, increasing to between 10^{-2} and 2.5×10^{-2} in the UV and IR wavelength regions [2].

Recent work has demonstrated the advantages of replacing lamp-monochromator sources with laser-based integrating-sphere sources [3-5]. These sources have several advantages over lamp-monochromator sources, including higher spectral radiant power, smaller errors arising from stray light, and a lower wavelength uncertainty. In addition, the integrating sphere is a nearly Lambertian source and is better suited in general for radiance and irradiance measurements than are monochromator-based sources. These advantages all contribute to reducing the uncertainties in irradiance and radiance calibrations. With laser-based sources, filter radiometers can be calibrated for irradiance or radiance responsivity with relative combined standard uncertainties of the order of 5×10^{-4} [5].

In addition to addressing current industrial needs, improvements in the national spectral power, irradiance and radiance responsivity scales will directly affect the derivation of fundamental photometric and radiometric units. At the NIST, for example, the photometric base unit, the candela, is currently realized and maintained on a set of standard reference photometers [6], and the lumen is now also realized using a detector-based system [7]. In each case, the dominant uncertainty component in the realization of the unit is the uncertainty in the spectral irradiance responsivity of the photometers. Development of a facility capable of detector irradiance responsivity calibrations at the 5×10^{-4} relative uncertainty level would lead to significant reductions in the uncertainties of the photometric units. Similar improvements would be realized in radiance temperature, spectral irradiance and radiance scales [3].

We have recently developed a laser integrating-sphere source and incorporated it into a new facility for Spectral Irradiance and Radiance Calibration with Uniform Sources (SIRCUS) [8, 9]. We briefly describe the facility in Section 2 and present results of calibrations of irradiance and radiance meters in Section 3.

2. Description of the facility

Figure 1 is a schematic diagram of the SIRCUS facility. In place of the standard lamp-monochromator source

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assembly, tuneable laser sources are directed into an integrating sphere. A number of tuneable and fixed-frequency lasers will ultimately be used to generate light over the spectral range 0.2 μm to 18 μm; details of the lasers developed for the facility are given in [8]. The output of the lasers is directed into an intensity stabilizer to reduce the magnitude of intensity fluctuations of the source, and into a wavemeter to measure the wavelength of the radiation. From there the radiation is sent through an iris, reflected off a vibrating mirror mounted on a galvanometer and sent through a lens into an integrating sphere (for irradiance and radiance response measurements) or directly on to detectors (for power response measurements). The vibrating mirror in front of the integrating sphere is used to reduce effects such as speckle that occur because of the coherence properties of laser radiation. The lens improves the uniformity of the radiance at the sphere exit port.

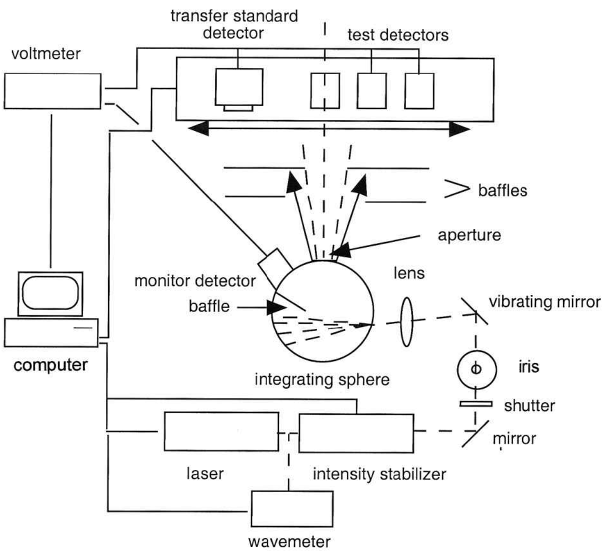

Figure 1. Schematic diagram of the Spectral Irradiance and Radiance Calibration with Uniform Sources (SIRCUS) facility.

The integrating sphere serves as a uniform, Lambertian source. We have a variety of integrating spheres for irradiance and radiance responsivity calibrations, ranging in size from 5 cm to 50 cm, and coated with two different materials – Spectralon for the UV through NIR, InfragoldLF for the IR – depending on their anticipated applications. Baffles are typically included in the integrating spheres to improve the uniformity of the radiance at the exit port. A monitor detector corrects for small fluctuations in source intensity during a calibration.

For irradiance and radiance responsivity calibrations, test sensors and a reference detector are located on a translation stage at a fixed (and known) distance from the sphere exit aperture. The test sensors are calibrated against the reference detector using the substitution method. A computer controls and monitors the laser power and wavelength over much of the spectral range, controls the positions of the detectors and sources, and records test and reference detector signals.

Table 1. Relative combined standard uncertainty of irradiance response calibrations on SIRCUS.

Uncertainty factor	100 × Type A	100 × Type B
Radiant intensity of source		
Trap spectral power response [10]		0.03
Trap aperture area [12]		0.01
Source-to-trap distance squared	0.05	
Trap repeatability	0.04	
Amplifier gain		0.04
Irradiance transfer to test detector		
Source-to-test distance squared	0.05	
Test detector repeatability	0.04	
Amplifier gain		0.04
Relative combined standard uncertainty	0.104	

The standard detector for the spectral range 406 nm to 920 nm is a silicon trap detector. Its radiant power responsivity is measured against the High Accuracy Cryogenic Radiometer (HACR) [10], the primary US standard for radiant power measurements, by direct substitution at several wavelengths. The trap detector responsivity at other wavelengths is determined using the physical model developed by Gentile et al. [10]. A high-precision aperture with known area is placed on the front of the trap detector; the product of the radiant power responsivity and the aperture area determines the irradiance responsivity of the trap detector.

To calibrate a test sensor on SIRCUS, laser radiation is introduced into the sphere at a particular wavelength. The reference standard detector is placed at a distance, D_1, from the integrating-sphere source and the irradiance, $E_1(\lambda)$ on the detector is measured. Knowing the irradiance on the reference standard detector and the distance D_1, we calculate the radiant intensity $I(\lambda)$ of the source: $I(\lambda) = E_1(\lambda) * D_1^2$. The test sensor is then moved in front of the sphere at a measured distance, D_2, from the sphere. The irradiance on the sensor, $E_2(\lambda)$ is given by the source radiant intensity divided by the distance D_2 squared: $E_2(\lambda) = I(\lambda)/D_2^2$. The test sensor signal, $S_{\mathrm{out}}(\lambda)$ is recorded, and the irradiance responsivity R calculated by taking the ratio $S_{\mathrm{out}}(\lambda)/E_2(\lambda)$ The wavelength of the laser is then changed, and the process repeated. Table 1 gives the relative combined standard uncertainty for the irradiance responsivity calibration of a test detector for the spectral range 406 nm to 920 nm. Our current relative uncertainty is approximately 10^{-3}, with the dominant sources of uncertainty being the source-to-detector distances and the measurement repeatability.

We have extended the scale to between 200 nm and 1800 nm using a newly developed pyroelectric radiometer [11]. The relative responsivity of the radiometer was first determined by measuring its reflectance over the full spectral range, and the absolute responsivity determined by comparison with the reference trap detector at several wavelengths in the visible spectral region. Owing to the additional step in the calibration chain, the relative uncertainty in irradiance responsivity increases to between 1.5×10^{-3} and 2×10^{-3} for the spectral ranges 325 nm to 406 nm and 920 nm to 1800 nm.

3. Applications

A number of instruments have been calibrated for radiance and irradiance response in the spectral range 406 nm to 920 nm, including broadband irradiance and radiance meters, narrowband filter radiometers (for both radiance and irradiance), and a charge-coupled-device (CCD) camera. We present representative results of calibrations of a broadband irradiance meter and a narrowband filter radiometer and compare them with previous calibrations.

3.1 Broadband irradiance meter calibration

A broadband, diffuser-type reference standard quality irradiance meter [2] was calibrated on the SIRCUS facility over the spectral range 406 nm to 920 nm. Figure 2 shows the irradiance responsivity of the instrument. It is informative to compare the SIRCUS calibration with results of a previous calibration on the lamp-monochromator system (SCF). The relative combined standard uncertainty in the SCF calibration was estimated to be approximately 5×10^{-3} over the spectral range 406 nm to 920 nm [2]. (Note the increased relative uncertainty in irradiance responsivity calibrations (5×10^{-3}) over radiant power responsivity calibrations (10^{-3}) on the SCF.) The agreement between the two facilities, shown in the inset to Figure 2, is better than their relative combined expanded uncertainty ($\boldsymbol{k} = \mathbf{2}$) of 10^{-2}. The irradiance response of the instrument measured on the SCF is approximately 0.5 % lower than the instrument's response measured on SIRCUS over the spectral range 450 nm to 900 nm. There is a sharp change in the difference between the two facilities at 420 nm that warrants further examination.

The new spectral irradiance responsivity calibration on SIRCUS has validated the irradiance responsivity measurements on the SCF and reduced the relative combined standard uncertainty in the irradiance responsivity of the instrument by a factor of 5, from 5×10^{-3} to 10^{-3}.

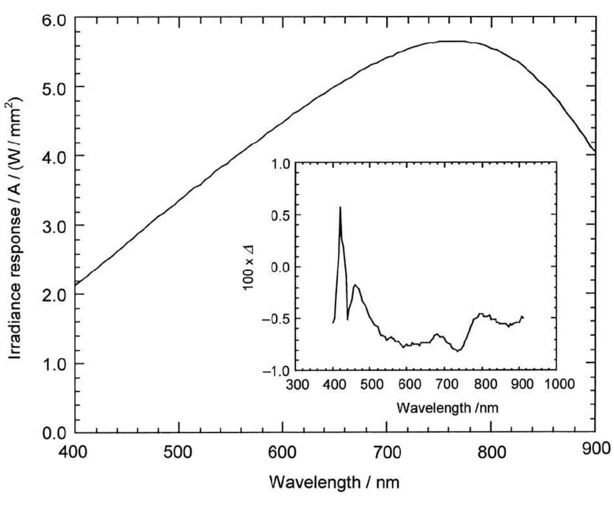

Figure 2. Irradiance responsivity of the diffuser-type radiometer measured on SIRCUS. Inset: the relative difference between irradiance responsivity measurements on SIRCUS and the Spectral Comparator Facility. Here $\Delta = (R_{\mathrm{SCF}}/R_{\mathrm{SIRCUS}}) - 1$, where R is the irradiance responsivity defined in the text.

3.2 Narrowband filter radiometer calibration

We have calibrated a number of narrowband filter radiometers on SIRCUS. One example is the Photoelectric Pyrometer (PEP), developed by the NIST for radiance temperature measurements [13]. The PEP is used as a ratio instrument to determine radiance temperatures of black bodies and tungsten filament lamps by comparison with the gold-freezing-point black body. Figure 3 shows the relative spectral responsivity of the PEP. It has a band-centre wavelength of 655.31 nm, with a full width half maximum bandwidth of 1.1 nm.

Smaller wavelength uncertainties and the larger dynamic range of measurements on SIRCUS contribute to a reduction in the relative combined standard uncertainty in the relative response of the PEP. The uncertainty in the wavelength scale on SIRCUS is approximately 0.005 nm, compared with a 0.01 nm wavelength uncertainty on the SCF. In addition, measurements on SIRCUS are inherently narrowband, and deconvolution of the responsivity to eliminate

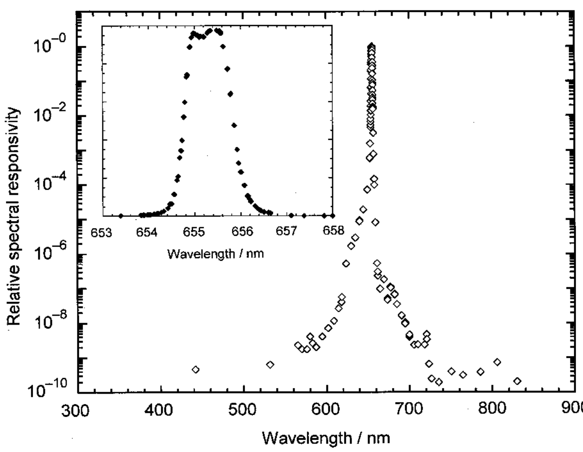

Figure 3. Relative spectral responsivity of the NIST Photoelectric Pyrometer (PEP). Inset: expanded view of the in-band responsivity.

effects associated with the 4 nm bandwidth of the SCF source is no longer necessary. The higher radiant power and lower stray light allow a larger dynamic range in out-of-band measurements on SIRCUS. The PEP measurements demonstrate a dynamic range on SIRCUS of nine decades, an improvement of 3 orders of magnitude over the SCF [13].

Interference effects arising from multiple reflections of the incident radiation in optical components within a radiometer can be a problem on SIRCUS. While we did not see any evidence of interference effects in the calibration of the PEP, they have been observed in the calibration of other filter radiometers. These effects can be eliminated in most cases by careful design of the optical system – for example, by using wedged elements in the radiometer. In measuring the out-of-band response of filter radiometers below the 10^{-7} level, care must be taken to account for and eliminate any source of background fluorescence. For example, in calibrating the PEP we eliminated residual fluorescence from the laser sources by dispersing the emission through a prism and sending the laser beam through an aperture prior to introducing the radiation into the integrating sphere.

4. Summary

The SIRCUS facility has several advantages over a conventional lamp-monochromator-based facility, such as the SCF, allowing irradiance or radiance responsivity calibrations with reduced uncertainties. We have demonstrated a reduction in the relative combined standard uncertainty in irradiance responsivity calibrations on SIRCUS compared with the SCF in the visible wavelength region by a factor of 5 – from 5×10^{-3} to 10^{-3}, with similar reductions in radiance responsivity calibrations. With minor improvements to the facility, we expect to reduce our relative uncertainties further – to the 5×10^{-4} level. These reductions in uncertainty will address current and future needs of our commercial customers, and will also reduce the uncertainties in US national radiometric and photometric scales.

Acknowledgements. We would like to acknowledge NIST colleagues T. C. Larason for measurements on the Spectral Comparator Facility and J. Houston for providing trap detector calibrations. This work was supported by the US Air Force Metrology under contract numbers 97-421 and 98-439.

Note. Identification of commercial equipment does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified is necessarily the best available for the purpose.

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